

Restoration Issues in Large Metropolitan Power Systems: An Example in the Berlin Distribution Grid

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Abstract—This paper presents results of a restoration field test carried out by the Distribution System Operator (DSO) in the city of Berlin. Based on a previous study, the company decided to use a gas-fired power plant with black start capability at the border of its service territory to start the restoration process in coordination with the Transmission System Operator (TSO). In a subsequent stage a larger combined cycle gas power plant located in the downtown area is intended to be brought into service. The test carried out included the start-up of the smaller unit, its connection to the larger power plant via a 110-kV line, synchronization of both generators, a short parallel operation, and identification of the minimum load on the smaller unit so that it would not trip by the reverse power protection upon synchronization with the larger unit. This paper reports on the experimental set-up and measurement results as well as the simulation study carried out afterward. The purpose of the simulation was to identify the corresponding dynamic models of the involved gas turbines and to verify the first crucial steps during the restoration process. Based on the experience with the Berlin distribution system the authors will provide some general recommendations concerning the autonomous restoration of supply to large metropolitan areas.

Index Terms—grid restoration, field test, model identification, dynamic study

I. INTRODUCTION

The authors reported in a previous paper [1] about the ongoing preparatory work by the local Distribution System Operators (DSO) in Berlin and Hamburg (Vattenfall Europe Distribution Berlin and Hamburg, respectively) to develop an autonomous system restoration strategy, which would rely only on the generation resources available within their respective service territories. Now that the simulation studies and the field tests have been completed and the concept formulated, this paper offers an insight into the details of the work conducted in the run-up period and the concept that emerged from it.

The distribution networks both in Berlin and Hamburg are directly connected to the 400-kV transmission network. The idea of an autonomous restoration using local generation

capability was prompted by the assumption that in the event of a major grid fault, waiting for the supply to resume via the grid is an uncertain prospect. Depending on the cause and nature of the blackout, the wider restoration process can under circumstances take a long time. Given the potential impact of a blackout for an extended period of time in large metropolitan areas, the proposition is that the local DSO should start to restore supply partially to critical public institutions and sensitive installations by mobilizing locally available resources (CHP) to the extent possible.

Since the methodology used to work out the restoration strategy for both Berlin and Hamburg is similar this paper focuses only on Berlin. The starting point for any autonomous strategy is a unit which survived the blackout and remained operational in an island mode or a unit with a black start capability which can be made operational in short order. It was decided beforehand that for Berlin any possible network restoration should start from a unit in the gas-fired plant denoted as GT-A in Fig. 1. This plant has a full black start capability and also a link to a 110-kV line. Once this generator is up and running, the next step envisions the start-up of a unit denoted as GT-M in Fig. 1 using power from GT-A. The plant GT-M is a 160-MVA gas-fired plant situated in the city center, also connected to the 110-kV grid. Once these two units are started and successfully synchronized to one another, they should be in a position to cover a sizeable load.

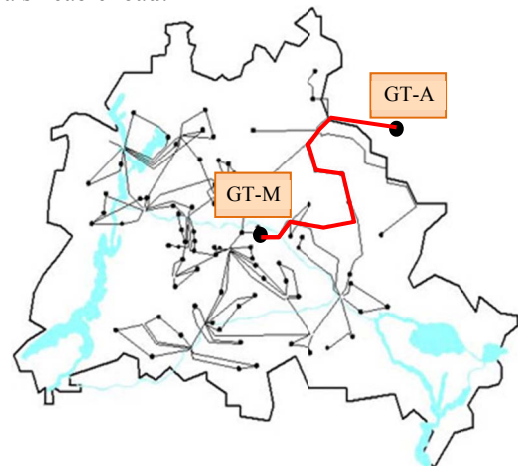


Fig. 1: 110 kV grid and location of the power plants to be used for restoration

To ascertain the technical feasibility of this restoration plan, Vattenfall Europe Distribution Berlin performed

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extensive field tests on both installations to identify the dynamic models. Moreover, the black start procedure at plant GT-A and its successful synchronization with GT-M was tested using field tests performed under conditions nearly similar with the real operational scenarios. With the identified and validated models, extensive simulation studies were then conducted, and the sequence of actions in the event of a real contingency deduced.

II. FIELD TEST AND MODEL IDENTIFICATION

The field test was performed in the following steps. First, a separated sub-network was formed by disconnecting the plant GT-A and the unit GT-M from the operational grid; the loads supplied by the stations along the 110-kV lines were transferred to other bus bars for the duration of the test (cf. Fig. 2). The 110-kV connection between the two points is approx. 25 km long, of which the major part is overhead line. The total reactive power generation along the stretch is about 6 Mvar.

Before the test an additional autonomous line protection system with adapted settings was installed since protection of the system with the standard protection settings could not be guaranteed due to the low short-circuit level in the test system.

The measurements of the field test were to be stored in high resolution data acquisition systems located in both power plants as well as in station F (cf. Fig. 2).

Initially the black start procedure went ahead as anticipated without any hitch. However, the generator circuit breaker was tripped by the reverse power protection repeatedly 2 to 3 s after the generator-transformer was energized. The startup process could only be continued by deactivating this protection during the energization of the transformer. One possible solution to overcome this problem is to energize generator and transformer together in one step.

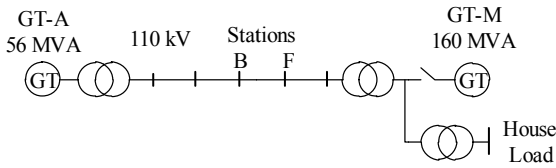


Fig. 2: Studied power system

Once the generator GT-A was successfully started, the next task was to link it up with unit GT-M by subsequent energization of the 110-kV lines. The connection between the two points was established using the full voltage. Then the voltage was reduced to 50 % of the rated value by lowering the excitation at GT-A to energize the 160-MVA transformer. This was deemed necessary due to the uncertainty regarding the level of inrush current. During the reduced voltage phase a distance protection led to tripping of the 110-kV line as a result of a current independent under-voltage setting which was set at 50% voltage. The protection relay was disabled. This relay was already scheduled to be replaced in the near future anyway, and the new replacement relay will allow adaptation (by changing the settings) to the requirements of any future restoration. The energization of

the transformer with 50% voltage took place without any problem. Motivated by this success the transformer energization was re-run with 80 % and then 100% voltage which all turned out to be successful. In all cases there was no protection system activity, and the peak switching currents remained a little below the rated current. Fig. 3 shows the recordings in station F. The inrush current through the 160-MVA transformer was simulated using the Netomac software [2]. Both results, shown in Fig. 3, exhibit good conformity with one another. The shift seen in the measured inrush current is due to the performance of the CT (a DT1 transfer function, actually), which was not taken into account in the simulation model.

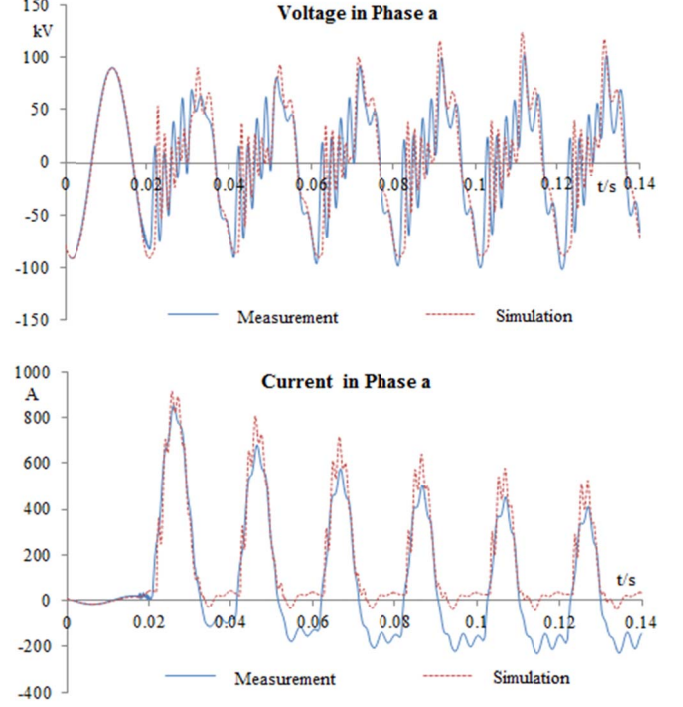


Fig. 3: Voltage and current following the energization of the 160-MVA transformer in power plant M. Measurement and simulation results in Station F.

The results obtained have led to the decision to perform any future restoration process following a contingency using the full voltage.

It should be pointed out that up to this stage the 110 kV-network was being operated without neutral grounding. The option of grounding was only available after the generator-transformer in the power plant M was energized successfully.

The next task was to study the behavior of the 160-MW generator during start-up in both gas and oil fired operation modes. Consideration of oil is necessary, should the gas supply fail in case of a major power outage. As a result start-up of unit GT-M with oil from a local storage is planned as a backup. During this test a cooling water pump malfunction resulting from reduced voltage was encountered during start-up. The voltage dip occurred while the turbines were being started. As a consequence in all subsequent experiments the voltage for the house load was increased to about 105%. For operation with natural gas, starting the gas compressor may result in considerable voltage drop on the supply feeder.

However, due to the increased voltage, the run up processes was successful and did not result in further malfunctions. Fig. 4 shows the real and reactive power measured in station F during the starting phase of the compressor motors. In Fig. 5 and Fig. 6 the voltage and frequency variations are shown. While the frequency in GT-A could be maintained within acceptable margin, the voltage dips to approx. 80 % of the rated value. Per Grid Code equipment connected to the house load (including the compressors) must remain operational at or above 80 % voltage. In fact the compressor was up and running in about 13 s without any problem and no protection system activity was observed in the process. This was possible probably because the voltage was previously raised to 11 kV (nominal voltage 10,5 kV).

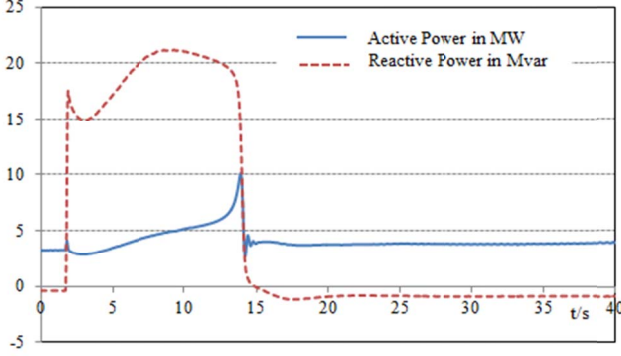


Fig. 4: Active and reactive power following start-up of compressor in GT-M. Measurement in Station F.

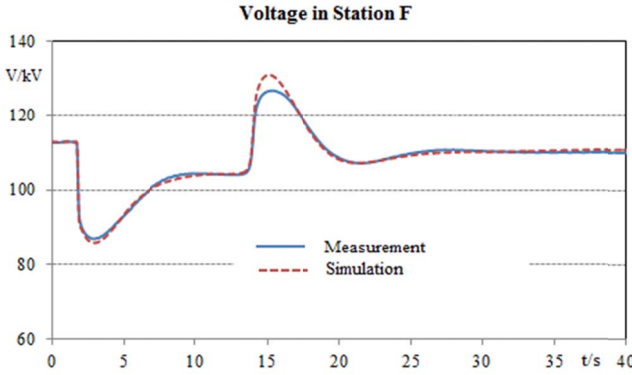


Fig. 5: Voltage in station in F following startup of compressor in GT-M measurement versus simulation results

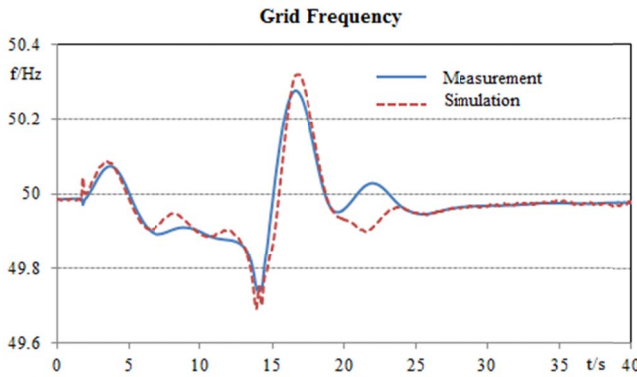


Fig. 6: Grid frequency following stat-up of compressor in GT-M.; measurement versus simulation results

The experiment was also utilized to derive the dynamic models and identify their parameters for both the governor and exciter of the unit GT-A. Fig. 5 and Fig. 6 show the comparison of the measured values with those obtained through simulation using the models. Both the exciter and the governor models were identified based on two measurements simultaneously. In addition to the already described compressor startup process, during an earlier test another motor in the house load circuit had been started and then switched off to obtain measurement results for simultaneous model identification. Due to space limitation the results of the second experiment will not be dwelt on here.

In spite of the good accuracy shown in Fig. 5, the experiment revealed that the response of the exciter of the unit GT-A deviates somewhat from the expected behavior. Consequently it is planned in the future to follow up on this and to try to unearth the cause of the discrepancy.

The next step was to find the models of the unit GT-M for simulation studies. In power station GT-M field tests for the purposes of determining the parameters of the exciter and governor models were carried out a few years back. Some of these models derived at that time could be used for the current restoration study. However, some of the tests were re-run particularly to ascertain the response in lower regions of power settings which is of particular interest in network restoration. A selected result is shown in Fig. 7.

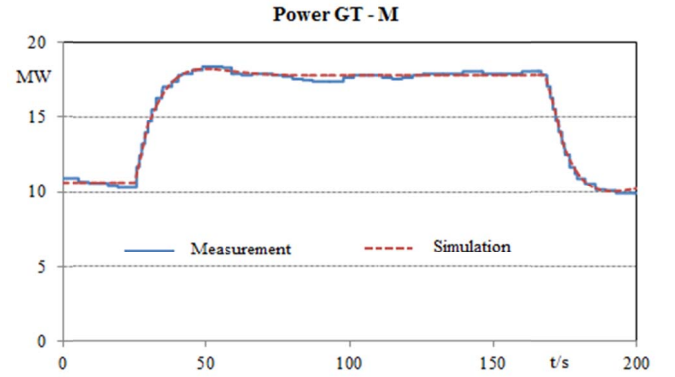


Fig. 7: Step response of GT-M to 10mHz change of reference frequency; measurement versus simulation results

In this experiment, after connecting the unit GT-M to the network, a small frequency deviation was superimposed on the frequency reference at the input of the speed controller to observe the step response. The results of the experiment reveal that the response of the turbine across its power range was dependent on the operating point and non-uniform, which makes any qualitative simulation difficult. However, since GT-A is primarily responsible for maintaining the frequency during parallel operation this uncertainty does not represent a major hindrance in the restoration process.

After GT-M was brought up to speed, both units were synchronized with one another. It was already known before the field test that the characteristic of GT-M was such that it would ramp up its output power to 6 MW in about 1-2 min after grid synchronization. The corresponding control could not be disabled for this experiment. Due to the fact that the base load in the network at this time was about 3 MW, it was

expected that the unit GT-A would resort to a motoring mode after GT-M increased the power. This indeed occurred and the unit was tripped after approx. 100 s by reverse power protection. One can deduce from this experiment that in the real world scenario GT-A would need to be sufficiently loaded first by connecting loads in the stations along the 110-kV line between the two power plants so that the addition of 6 MW would not lead to tripping. A simulation example related to this will be shown in the next section.

III. SIMULATION STUDY

As stated previously, the purpose of this simulation study was to gain insight into the performance behavior of the network in the initial stage of the restoration under load. In this regard the following two operational conditions are to be studied in detail.

- Unit GT-A operating alone; loads along the 110-kV line connected
- Both units (GT-A and GT-M) operational and covering the load increase jointly

Additionally, the synchronization process itself and the load shift from GT-M to GT-A was also of interest. The simulation was intended to give insight into the behavior of the system in all these scenarios.

In the restoration study it is important to represent the loads picked up in each stage as realistically as possible. The dynamic characteristic of loads depends on the composition of consumers connected to the feeder. Additionally, this characteristic is time variant. The model to be used therefore should reflect this relationship accurately to the extent possible. The step response of load model used in this study is shown in Fig. 8. The real and reactive powers are normalized on the respective rated values. The voltage dependency of the load was considered additionally during the simulation (exponential load model) since the depth of the voltage dip can change with the location of the load.

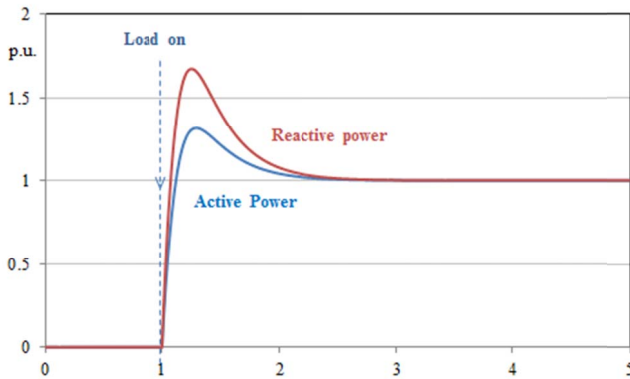


Fig. 8: Characteristic behavior of the simulated loads

A. Pick-Up of Loads by GT-A

As stated before a certain level of load on the unit GT-A is a necessary condition for its successful synchronization with the unit GT-M and to preclude the possibility of tripping after synchronization. During the course of the loading process it is interesting to find out the maximum load to be connected at any given moment so that the resulting voltage and frequency drops are not too high. It is also necessary to

know how fast the transient processes following a load switching settle to a new steady state value. In Fig. 9 the simulation results for a load pick-up by GT-A are shown.

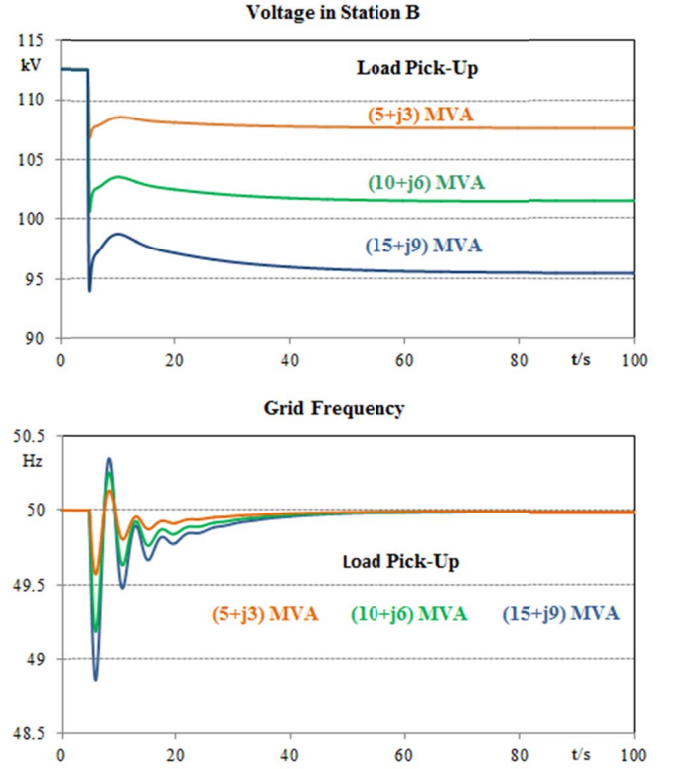


Fig. 9: Load pick-up by GT-A from no load conditions

The test results lead to the conclusion that the load to be switched to the network under consideration should not exceed 10 MW when GT-A is running alone. If this is the case the voltage and frequency decreases remain within the acceptable range, including a margin of safety to account for uncertainty arising from load controller behaviors. Before the load pick-up the load on GT-A in the simulated scenario was nearly zero, which represents the most critical scenario. Once a certain base load is connected, the voltage and frequency drops are less significant. The process attains steady state values in approx. 60 s, leading to the conclusion that load switching can occur in cycles of about one minute.

B. Synchronization of GT-A with GT-M

As opposed to the field test one can assume that the GT-A is already loaded prior to synchronization in a real case scenario. For this simulation a 15-MW load at a power factor corresponding to 5 Mvar reactive load was connected in one of the stations linked to the 110-kV line. The reactive load is almost fully compensated by the line capacitance. The synchronization took place at 10^0 voltage phase angle difference so that a short transient phase ensues following the interconnection. The results of the transient process following the synchronization are shown in Fig. 10. In line with expectations, the output power of the unit GT-M rises to 6 MW. Since no additional load was connected in the intervening period, the load on the unit GT-A drops as a result.

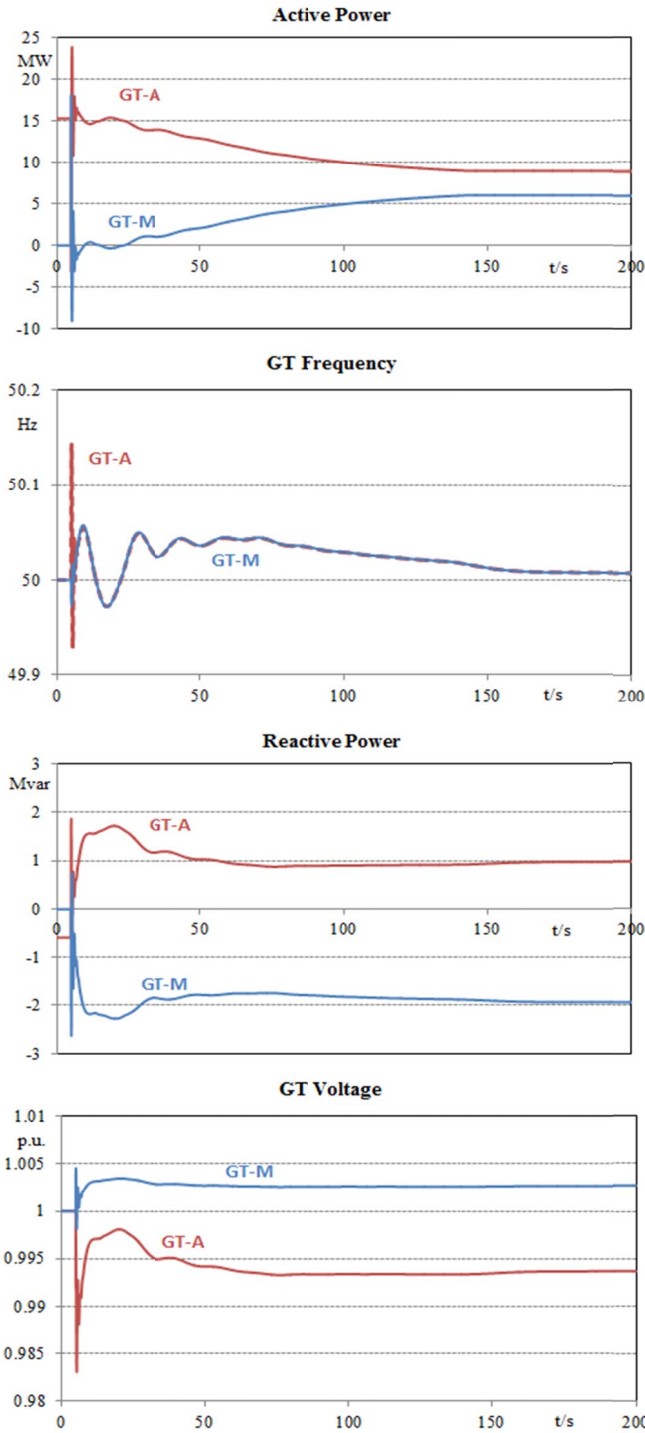


Fig. 10: Synchronization of both GTs and subsequent load pick-up by GT-M

The frequency and thus rotational speed of both generators become practically identical only after a short period of time. The frequency excursion is small and can be attributed to the finite reaction capability of both governors. The reactive power output adjusts itself in accordance with the response of the voltage controller. As a result of the increased power output in one end and reduction in the other end of the line, the movement of the turbine actuators in both generators are in opposing directions. The effect of this on the voltage is minimal. In general, it can be concluded that in

the presence of some base load on the unit GT-A the synchronization of both generators as a part of any eventual restoration process is not critical.

C. Joint Load Pick-Up of GT-A and GT-M

When both generators are already connected to the network and are operational, loading of the generators becomes decidedly less problematic due to the increased inertia and the fact that both generators are contributing to frequency control. In Fig. 11 the connection of a (10+j6) MVA load to both generators is shown.

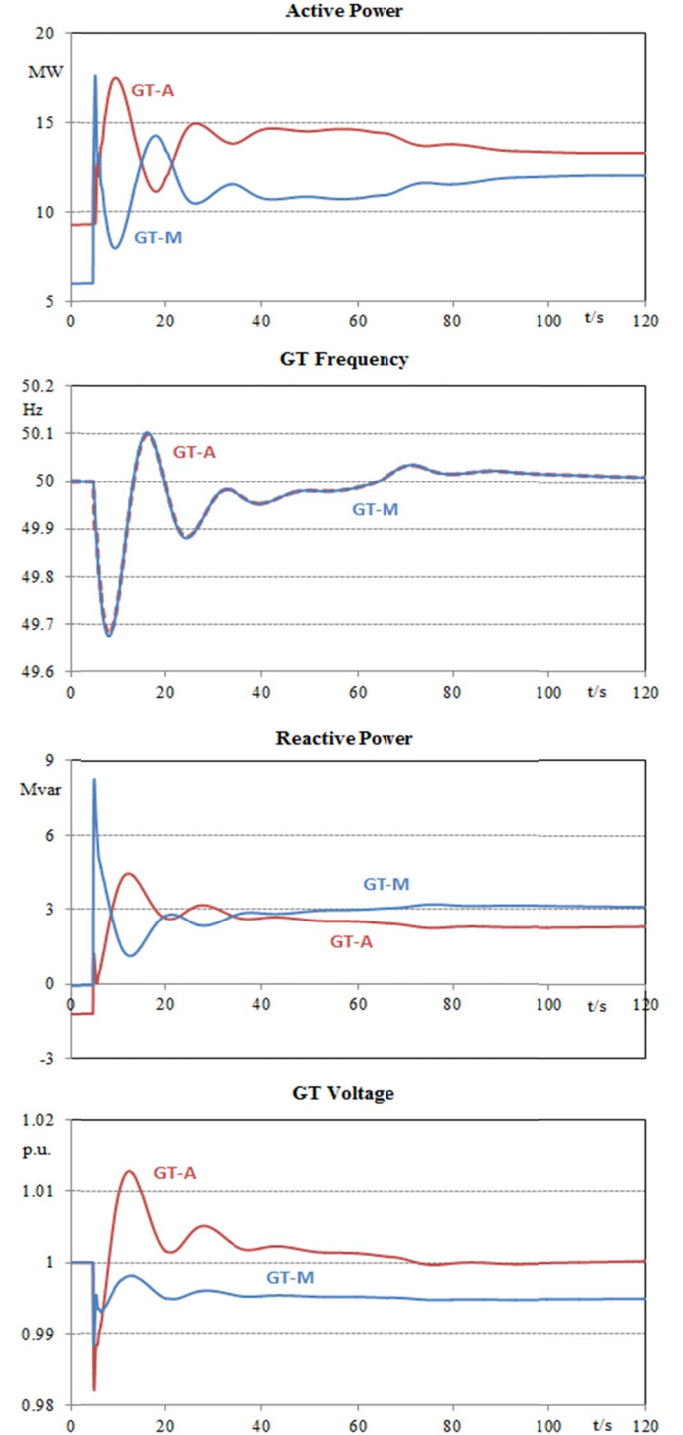


Fig. 11: Joint pick-up of (10+j6) MVA load by GT-A and GT-M

The minimum frequency is 49.68 Hz (compare this behavior with Fig. 9 where only GT-A is running). Both generators exhibit a coherent behavior so that there is only one single frequency. The two governors seem to operate at cross-purposes so that active power outputs oscillate slightly against one another. The amplitude of this oscillation however is small and exhibits a good damped behavior. The whole process is completed within two minutes.

As can be observed in the diagram, the load sharing between the two generators is not as expected, i.e. in ratio corresponding to their ratings (approx. 1:3) but share the load approximately equally. While the larger machine takes a slightly larger share of active power, the reactive power sharing is almost identical. One can deduce from this behavior the necessity of a manual correction in certain intervals during the restoration process. Fig. 12 shows the frequency characteristics at different levels of loading.

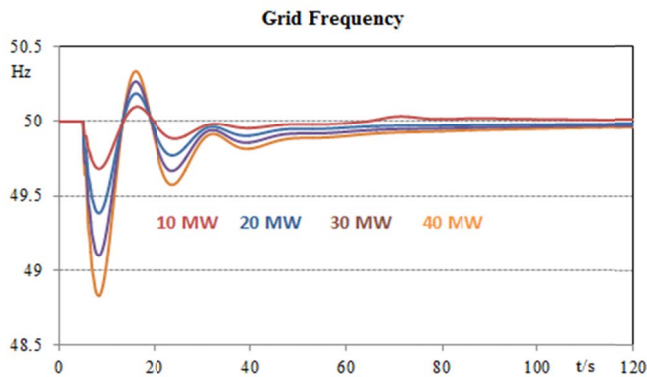


Fig. 12: Frequency response for different level of loading

As can be seen in Fig. 12 the frequency dips below 49 Hz only when the load picked up exceeds 30-35 MW. As a result, during the restoration procedure a relatively large load can be switched-on in each step.

IV. CONCLUSIONS

The field test – in addition to enabling the identification of the most crucial steps in the restoration process – formed the basis for the identification of governor and AVR models. This opened-up the possibility to conduct detailed simulation studies to understand the potential risks in each stage of the restoration process. The critical steps to be studied and validated against measurement results were the start-up process for each unit individually and the response of both units following loading in parallel operation. Although the numerical results obtained and the conclusions deduced are unique to the network under consideration, the methodological approach and the identified crucial steps can be considered as general.

The field test has revealed that the setting of the protection system can interfere with the start-up process and can possibly hamper the initial stages of the restoration. Plans regarding which settings of the protection relays are to be adapted or deactivated during the initial stages of the system restoration and the potential risks to the network arising from it should be identified. In the field test introduced in this

paper some of the problems were anticipated beforehand. For example, it was decided to use a protection system with adapted settings since protection of the system with the standard settings could not be guaranteed.

The field test has shown also the necessity of increasing the voltage level at the house load busbar before starting of large drives to ensure that the voltage drop will not result in tripping. Due to the small rating of the generator supplying the system the voltage sag may be larger than usual in grid connected operation.

The results of the simulation study formed the basis for deducing the minimum load on the first generator to be started before the next generator is synchronized to it. If the synchronization takes place before the first generator picks up sufficient load, the synchronization may fail due to reverse power protection. Apart from the synchronization process itself, ascertaining that the load transfer from one unit to the other does not lead to the tripping of any of the generators is necessary. A detailed simulation study augmented by field test should establish the maximum load that can be switched at time without violating frequency or voltage limits.

It was also observed during the tests conducted that the load sharing between the two generators was not as expected, i.e. not in ratio corresponding to their ratings but share the load approximately equally. While the larger machine takes a slightly larger share, the reactive power sharing is almost identical. The conclusion to be deduced from this behaviour is the necessity of a manual correction in certain intervals during the restoration process. The experiences acquired in the simulation studies and the accompanying field tests will form the basis for a handbook for operational staff, which will serve as a “recipe” for the sequence of activities following a contingency situation.

V. REFERENCES

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VI. BIOGRAPHIES



István Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he has been Professor and head of the Institute of Electrical Power Systems at the University of Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modeling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and senior member of IEEE.



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